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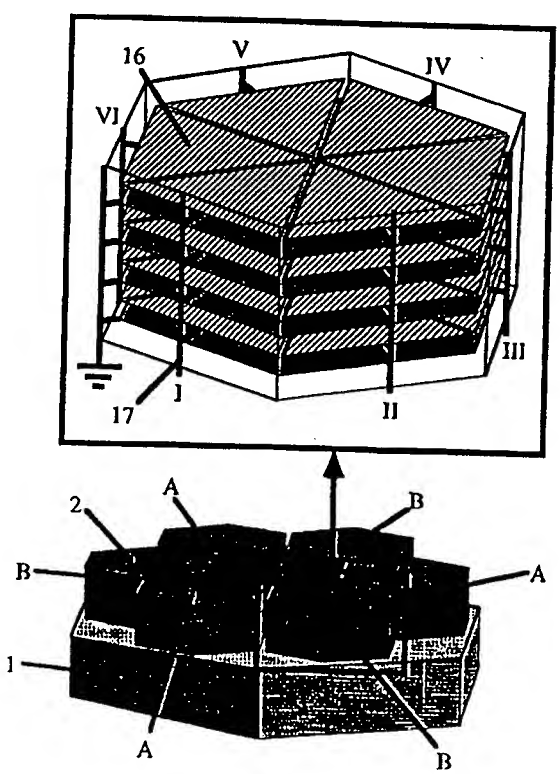
**Published**
*With international search report.*

(54) Title: AN ACTUATOR MOTOR AND A METHOD FOR FABRICATION OF SUCH AN ACTUATOR

(57) Abstract

This invention relates to an actuator or motor comprising an electromechanical material which alters its shape under the influence of an electrical voltage. Said actuator comprises at least a monolithic module (1, 2) with electrodes integrated in said electromechanical material and in that the force or displacement due to the applied voltages is transferred, to the point to be actuated or moved by the shape change of the material, using at least two independent contact points. The invention also relates to a method for fabricating said actuator or motor.



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An actuator motor and a method for fabrication of such an actuator.

## Technical field of the invention

The invention relates to small motors and actuators as set forth in the preamble of the appended main claim. The invention also relates to a method for manufacturing the motors according to the invention.

## Description of the background art

There is a great need for high performance motors in the size range below a few millimetres, motors of the kind which should be able to create linear and/or rotating motion. It is often desirable that this kind of motors both have a high precision and can exert large forces. One particular actuation principle which has a great potential to fulfil these demands is an inchworm type of motor (M. Bexell, A.-L. Tiensuu, J.-Å. Schweitz, J. Söderkvist, and S. Johansson, Sensors and Actuators A, 43 (1994) 322-329). The motion is created by repetition of small steps in a similar way to the insect inchworm, hence the name (The micropositioning book. Fishers, NY: Burleigh Instruments, Inc. (1990) ). There are some crucial factors limiting the development of existing products based on this type of motion principle. Among the limits are the difficulty of achieving a sufficient stroke of the individual actuating elements and the need for costly high precision assembly of the elements and other parts in the system. Some solutions to these problems have been

presented in the Swedish patent application No 9300305-1 (1993) Johansson. Using actuating elements with at least two-axial motion capacity the number of elements have been reduced. At the same time motion magnification by internal levers (e.g. bimorphs) in the elements can be included which gives a large freedom in design. A motor has been built according to these ideas and has proven to give the desired high torque and motion capacity as predicted (M. Bexell and S. Johansson, Transducers, Stockholm, Sweden (1995) 528-News). This motor gives at present the highest torque per volume of all miniature motors in the world. There are some disadvantages with this construction which is the origin for the present invention. In the previous patent application the motor for instance consisted of active elements mounted on a substrate, and typically soldering has been used as the assembling method. This is a fairly time consuming operation and therefore costly. Most applications demand however that the price of each motor should be very low.

## Brief description of the inventive concept

A particularly attractive solution to the problems described above associated with motors as defined introductorily is set forth in the characterizing part of the main claim. Preferred embodiments are set forth in the dependent claims.

## Brief description of the drawings

The invention will now be described in more detail with reference to the accompanying drawings, in which

Figure 1 is a preferred embodiment of a hexagonal, monolithic structure according to the invention,

Figure 2 illustrates an embodiment in the form of a tube, with controllable shape,

Figure 3 is a variant of the embodiment according to Fig 2 including a concentric inner tube with a peristaltic movement;

Figure 4 shows an embodiment allowing a combined rotating and linear motion,

Figure 5 shows an arch-shaped structure with an improved force capacity for a given stroke magnification,

Figure 6 illustrates a design with a minimized hysteresis effect and which is prepared for digital electronics,

Figure 7 illustrates a rolling process to define the shape of a electroactive tape,

Figure 8 shows some of the resulting geometries of a plastically deformed tape of electroactive material coated with an electrode layer.

Figure 9 shows a futher method of producing an actuator according to the invention.

Figure 10 shows alignment geometries in films used as starting materials.

## Detailed description of preferred embodiments of the invention

A preferred embodiment of the invention is illustrated in Fig 1, which shows a monolithic module integrating all the active elements. The monolithic module can be described in terms of a larger hexagonal mechanically passive part 1 and active elements 2 which are an integral part of the module. Each element consists of an electromechanical material, preferably piezoelectric, which typically is a multilayered structure. The electrical contacts 17 I - 17 VI are connected with electrode 16 and earth layers in between the electromechanical layers in the figure. One of the advantages with this layered structure is that the necessary voltages to achieve a particular electrical field becomes lower which is desired for the matching of the structure with e.g. the drive electronics. The use of electrode arrangements such as in Fig. 1 allows the element top surface to move arbitrarily in space relative to the substrate. If there are at least two independent active element sets, arranged for instance as A and B in Fig. 1, then the module can easily be used in an inchworm type of motor. Typically all elements are driven with sinusoidal voltages to achieve an elliptical motion of the element contact point relative to the substrate. For two sets A and B are typically rotating out of phase 180 degrees. For each element there are at least two phases and an simple arrangement in Fig. 1 would be to drive electrodes I and VI with one sinus wave and III and IV with another. These should

be phase shifted about 90 degrees. There are of course numerous ways to arrange the electrodes in the active elements. It is also desirable to integrate the control electronics generating the phase shifted voltages as well as various sensor (e.g. force position) feed-back and communication electronics into the integrated module.

One important application for miniature motors is in catheter type of instruments (for medical use). The problem is how to control the shape of a long narrow tube. Assuming that control and communication electronics are integrated within (or mounted on) the module an arrangements such as shown e.g. in Fig. 2 solves this problem. The whole module 1 has a wedge shape, typically with the back side 3 tilted. If the modules are rotated relative to each other, a tilting action results. Two modules operating together can create rotation without tilting. The wedge shape could be either the module itself or a separate unit, free or mounted on the module. It is also convenient to use an elastic material or an elastic structure (e.g. spring type of geometry) in-between or as the wedge-shaped unit. One possible solution for the assembling of such a system would be to enclose them into a bellow-shaped tube 4 creating the normal force in-between the many modules. All modules could be connected with one serial communication bus (e.g. 2-4 electrical wires) to reduce the number of electrical connections between the modules.

Another elegant catheter design is to use modules with a spherical contact surface, Fig. 3. The spherical contact surface 5 makes it possible to rotate each module relative to the next without any tilting. It is also possible to tilt each module in any direction if three-axial active elements are used. The catheter will be more flexible in comparison with the previous design, Fig. 2. The wedge shaped design is however much easier to manufacture which might be an advantage in some applications. There is also a desire to transport for instance liquids in and out through the catheter working end. This could be achieved with a tube 6 in the centre of the modules, Fig. 3. A peristaltic type of liquid transport can be made if two tube constrictions 7, spaced apart a certain distance, are moving together. Constrictions can be made by tube rotation or stretching using the modules.

Among the high performance applications are e.g. linear motion in fast, high precision equipment. One such design is shown in Fig. 4. It consists of three modules assembled into a stator structure 8. The stator structure has a geometry that creates a radial force against the rotor 10 by spring type elements 9. If the active elements in the module are made for three-axial motion as indicated in the figure, then both axial motion and rotation of the rotor can be achieved. A simple rotating motor can be constructed in an analogous way using two spring loaded structures similar to those of Fig. 1 with a rotor in the middle. The normal force necessary to create motion in between the stator and rotor can be

achieved in many ways. All types of forces can be used: gravitation, magnetic, electrostatic, molecular, atomic, viscous forces. The elastic forces in springs are of course attractive for many application but the use of permanent magnets might be one of the most cost-efficient methods.

The motion range of each active element in the modules is an extremely important parameter. There are competing motor types, usually called ultrasonic or travelling wave motors, used at centimetre scale at present. They are all based on the fact that if a structure is vibrated at the resonance frequency, the motion amplitude will be much amplified. It is however very difficult to achieve a satisfying performance of ultrasonic motors when they are scaled down to millimetre or smaller sizes. The problem is connected with the motion range of the moving parts in the motors. The same is true also for the present invention. A large enough motion range in relation to the fabrication precision and accuracy is needed. While the element construction given in Fig. 1 might be sufficient for certain motor sizes, some stroke magnification mechanism must be used when the motor is further miniaturised.

In the Swedish patent application mentioned above, bimorph elements were used to obtain two-axial motion and at the same time possibility for stroke magnification. The disadvantage with a single clamped bimorph is that the force capacity is greatly reduced in comparison with an ideal lever. A double

clamped bimorph, a curved membrane or an arch-shaped structure 12 as in Fig. 5 have a better force capacity for a given stroke magnification. No completely satisfying designs for these leverage structures have been presented yet. Either they are to expensive to produce (for instance assembling) or the performance is not sufficient. The leverage structure 11 schematically presented in Fig. 5 solves all these problems. It is a monolithic body consisting of arch-shaped structures arranged with two oppositely oriented arches 12 as a base unit. The arches are typically electro-active material with layers of electrodes and connected in such a way that, for a given applied voltage, one arch increases and the other arch decreases its curvature. In that way the whole body will expand in the vertical direction and horizontal forces 14 will be compensated. By intelligent distribution of the electrodes in the module three-axial motion can be achieved. The volume in between the arches could either be empty or filled with suitable elastic material.

Another critical problem encountered when actuators are constructed with electro-mechanic materials such as piezoceramics is the large hysteresis: the expansion of the material not only depends on the voltage applied but also on factors such as time and voltage history. There is one way to minimize these effects and at the same time prepare the active element for digital electronics. In Fig.6 a elegant solution to these problems is schematically presented. Instead of using an analogue voltage to control the material

expansion, fixed voltages are applied to some or all contacts. Each particular contact is connected with a particular number of (or parts of) electrode layers 16. This number determines how many layers of electro-mechanic material 15 that are active for a specific contact 17 and is chosen to be the corresponding values for each digit in the binary number system. For instance contact 0 corresponds to digit (bit) number 0, hence $2^0=1$ electrode layers are connected to this contact. Contact 1 with $2^1 = 2$ electrode layers etc. Using this contact code, the number of active layers for a given combination of contacts with applied voltage can be calculated as the value in the binary number system assigning 1 if voltage is applied and 0 if not. The expansion of the material is proportional to the number of active layers and hence to the binary number. Also parts of layers can be used to e.g. improve resolution. The hysteresis of the material is minimised by the switching between a fixed voltage and ground instead of applying an analogue voltage. Undesired resonances in the structure by the fast voltage changes can be damped by adjusting the resistance of the electrode layers. The resistance in series with the capacitance of the structure will become a low-pass filter.

In a major part of the future applications for miniature motors the fabrication has to be cheap. Present microfabrication techniques are rather expensive and yet far from suited to make cheap active components. The main needs are electrode patterning and electric interlayer connection in the elec-

troactive material. There is of cource a desire to directly form the monolithic module to its final shape, including internal voids or similar. Some possible processing techniques to solve these problems are described in Figs. 7-10. In Fig. 7 rollers 18 with geometrical shapes 19 are used for replication of these shapes into a tape with electro-mechanic material 15. An alternative to rollers is to use the somewhat slower stamping process, which has the advantage of a cheaper tool fabrication. If the tape is already covered with electrode layers 16, either on one or on both sides, the patterning of the electrodes can be made directly by the rolling process, Fig. 8 the electrode layer is divided by plastic deformation of the tape resulting in separate electrode areas. The electrode patterning on top of e.g. a polymer tape with piezoelectric grains is normally difficult by standard litographic techniques and this method solves this problem in an elegant way. Electrical connection between the layers could be made by formation of holes 20 by plastic deformation of the tape. Another method would be to use rolling, Fig. 9, folding, twisting etc. in combination with plastic deformation to achive desired electrical connection. Subsequent processing steps are to laminate these layers and by heat treatment produce a monolitic unit or module. Internal void volumes (or suitable material) could be made by including layers with non-electroactive material. During heat-treatment a polymer material would disappear, for instance. External friction layers etc. could be included in the same way. Alignment during lamination can be greatly

simplified if particular alignment geometries, e.g. peg in hole, also are replicated in the film (Fig.10)

It should be noted that the invention naturally may be varied in many ways within the scope of the appended claims.

## CLAIMS

1. An actuator or motor comprising an electromechanical material which alters its shape under the influence of an electrical voltage, **characterized in that** said actuator comprises at least a monolitic module (1,2) with electrodes integrated in said electromechanical material and in that the force or displacement due to the applied voltages is transferred, to the point to be actuated or moved by the shape change of the material, using at least two independent contact points.

2. An actuator according to claim 1, **characterized in that** electrical contacts (17I-17VI) are connected in such a way with the electrodes that particular shape changes can be obtained for each electric contact (17I-17VI).

3. An actuator according to claim 2, **characterized in that** each contact (17I-17VI) represents a digit in the binary number system and the contacts (17I-17VI) are connected to the corresponding number of electrode layers as the value of each digit.

4. An actuator according to claim 2, **characterized in that** each contact (17I-17VI) represents a digit in the binary number system and the contacts are connected to electrode (16) areas which give a mechanical deformation proportional to the corresponding value of each digit.

5. An actuator according to claim 1 **characterized in that** three dimensional cavities are integrated (formed) in the module to create an internal leverage and the cavities could be either empty or filled with an adequate material.

6. An actuator according to claim 5 **characterized in that** the base unit of the module consists of structures (12) which are curved in two or in three dimensions and which are shaped in such a way as to minimize undesired forces (14) or displacements.

7. An actuator according to claim 5 **characterized in that** the internal leverage is based on arch-shaped structures (12) which are fixed at least at two ends, the force and displacement transfer being located at the central portion of the arch.

8. An actuator according to claim 5, **characterized in that** curved membranes or plate structures are used to obtain said internal leverage.

9. An actuator according to claim 5, **characterized in that** said cavities are filled with a rubber-like material.

10. An actuator according to claim 1 **characterized in that** said contact points can be positioned independently of each other arbitrarily in space and that said module (1,2) by itself or in combination with other modules (1,2), can be used for relative motion of another body, called rotor (10).

11. An actuator according to claim 10 **characterized in that** the contact points of the active elements are located in a plane which is inclined relative to the base plane of the module or an attached unit.

12. An actuator according to claim 10 **characterized in that** each active element can be positioned in two independent directions.

13. An actuator according to claim 10 with a spherical contact geometry of the active elements and a corresponding spherical surface in the base part of the module or an attached unit.

14. An actuator system comprising of a number of modules according to claim 10.

15. An actuator system according to claim 14 where a bellow-shaped tube is used e.g. to create the normal force between the modules.

16. An actuator according to claim 14 where a central tube (6) is used for transport of e.g. liquids and where the transport is made by a peristaltic motion (17) due to moving constrictions controlled by modules.

17. An actuator according to claim 10, **characterized in that** said rotor (10) is pressed against the contact points.

18. An actuator according to claim 17, **characterized in that** said rotor (10) is pressed against the contact points with magnetic forces.

19. An actuator according to claim 17, **characterized in that** said rotor (10) is pressed against the contact points with elastic spring forces.

20. An actuator system comprising at least two modules according to claim 17, **characterized in that** said modules are pressed against a rotor (10) by external forces and where the active elements are used for at least two axial motions of the rotor.

21. An actuator system comprising of at least one module according to claim 18, **characterized in that** a rotor (10) is pressed against the active elements by a permanent magnet.

22. An actuator system comprising of two or more modules according to claim 11, **characterized in that** a rotative motion is transferred to a tilting motion.

23. An actuator according to claim 11 or 13, **characterized in that** a central tube (6) is used for transport of e.g. liquids and where the transport is made by a peristaltic motion (7) due to moving constrictions controlled by the modules.

24. An actuator system according to claim 11 or 13, **characterized in that** a bellow-shaped tube (4) is used to create the normal force between the modules.

25. A method for fabricating an actuator according to claim 1 based on replication of a geometrical pattern into a film including an electromechanic material which is coated with an electrode layer, by which means also a three dimensional patterning of the electrode is obtained.

26. A method for fabricating an actuator according to claim 1 based on replication of a geometrical pattern into a film where the geometrical shapes of the surface is used for alignment of one layer with another.

27. A method for fabricating an actuator according to claim 1 based on replication of a geometrical pattern into a film resulting in electrical via-holes through the film.

28. A method for fabricating an actuator according to claim 1 where the connection of electrode layers is accomplished with plastic deformation processes.

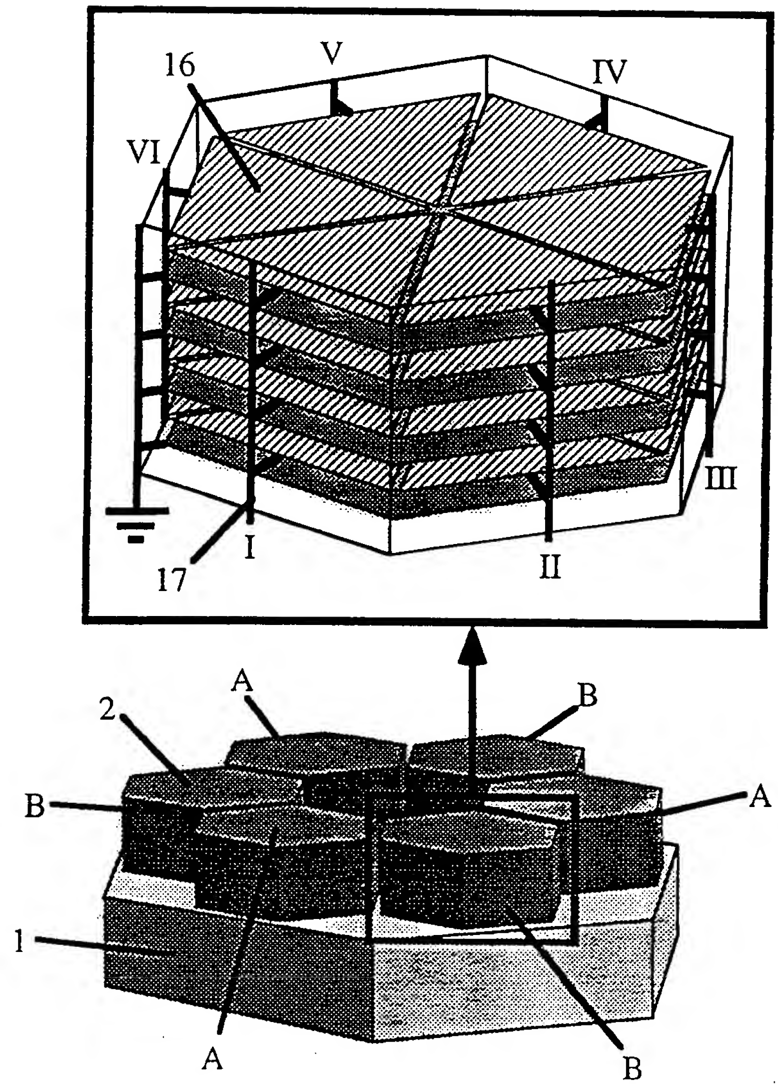



Figure 1

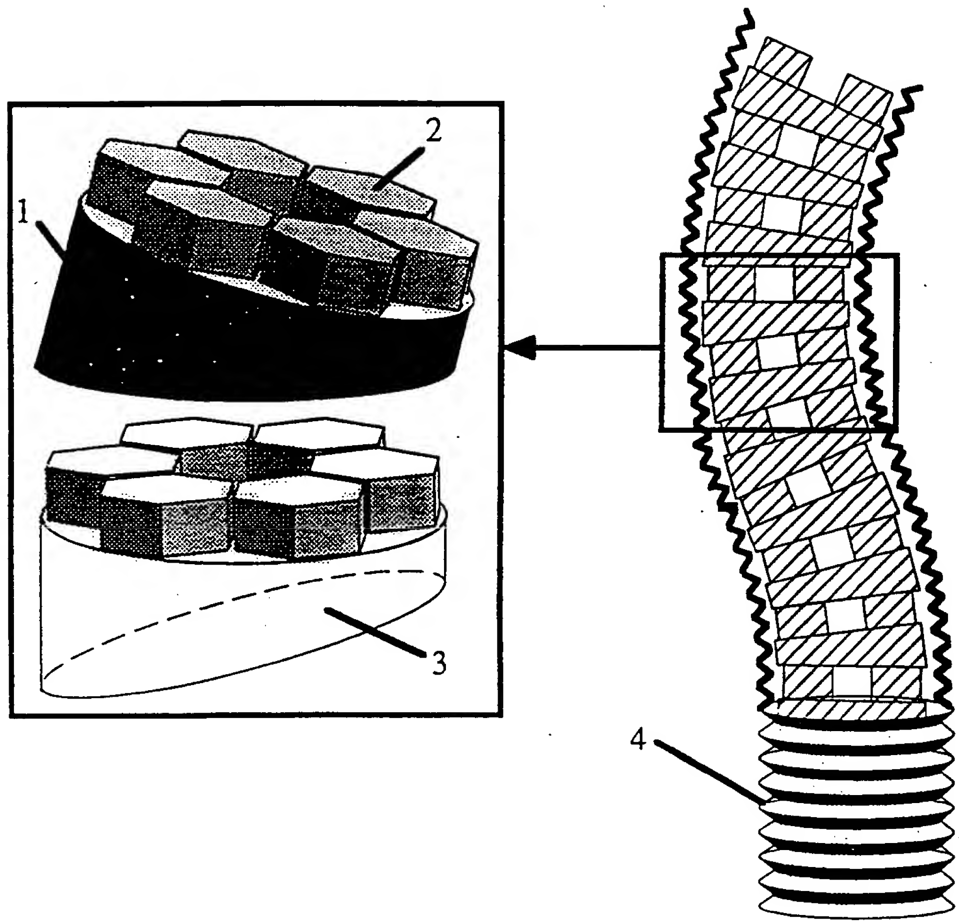



Figure 2

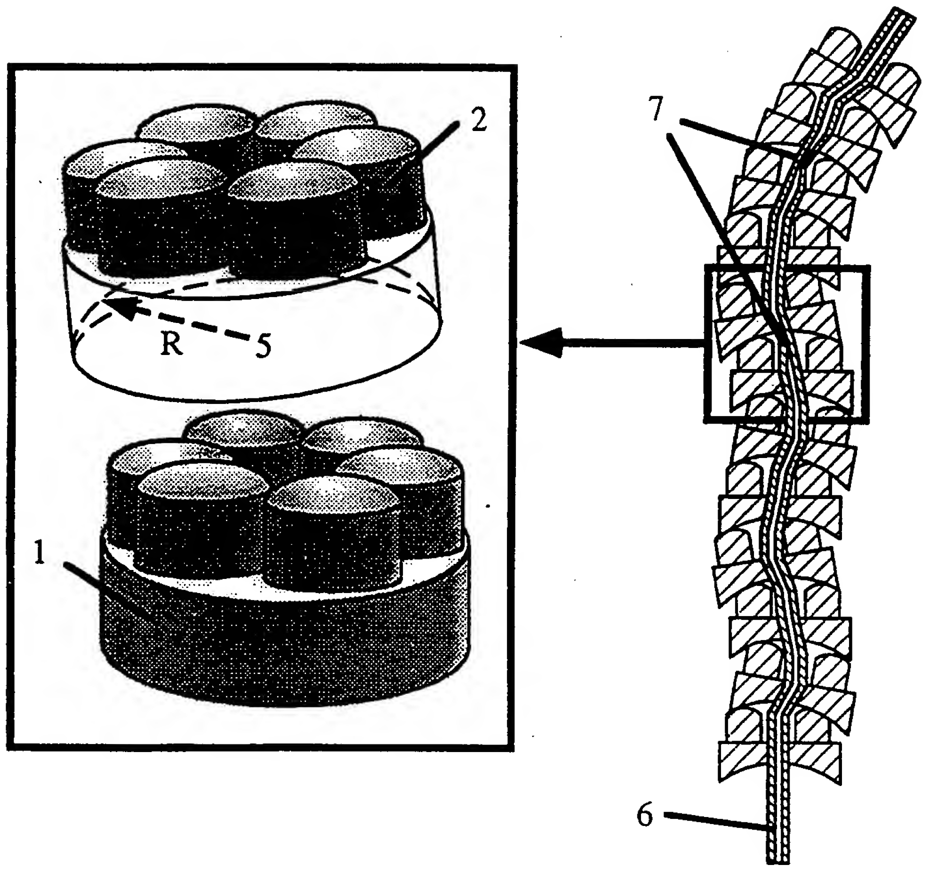



Figure 3

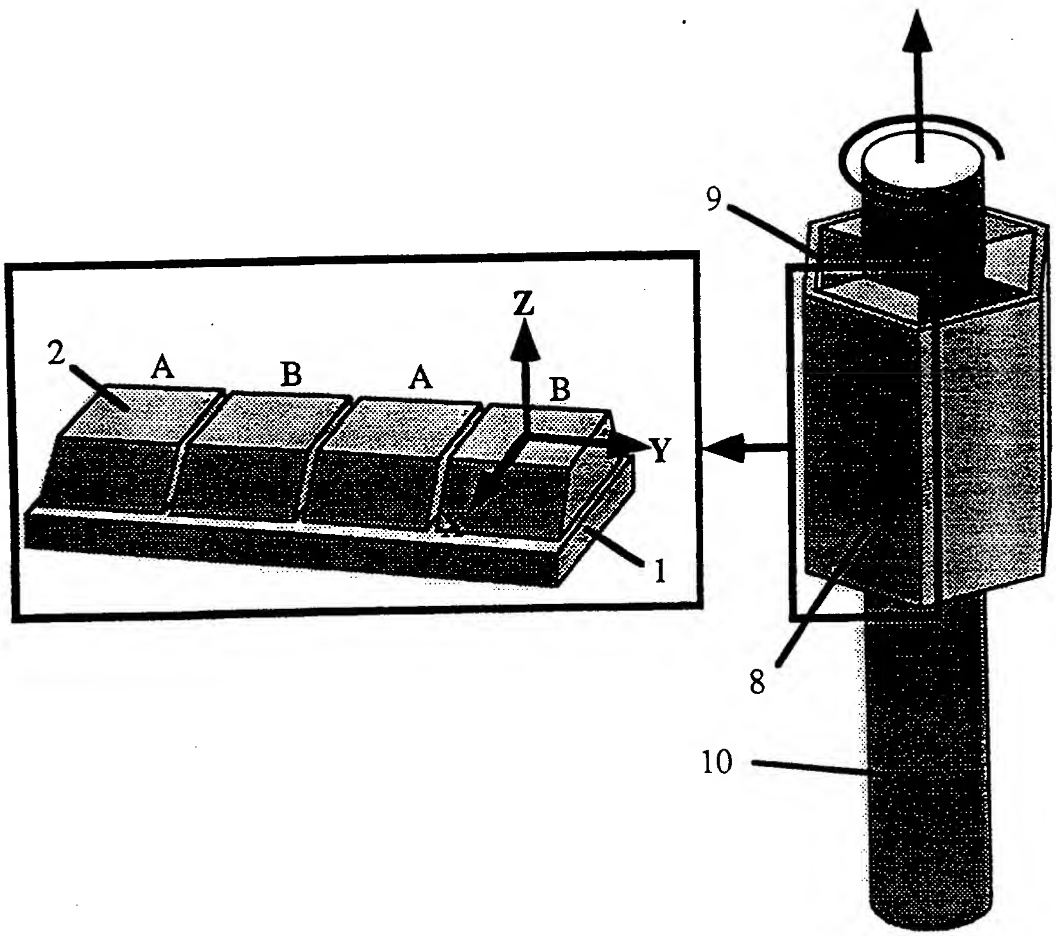



Figure 4

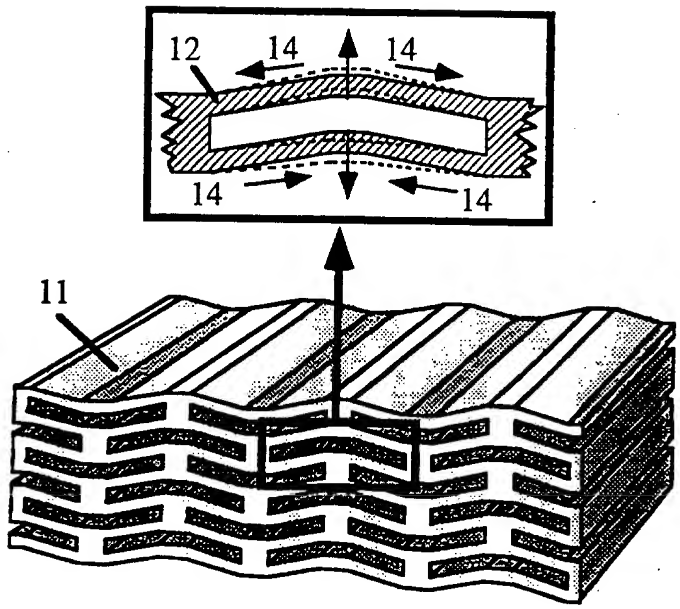
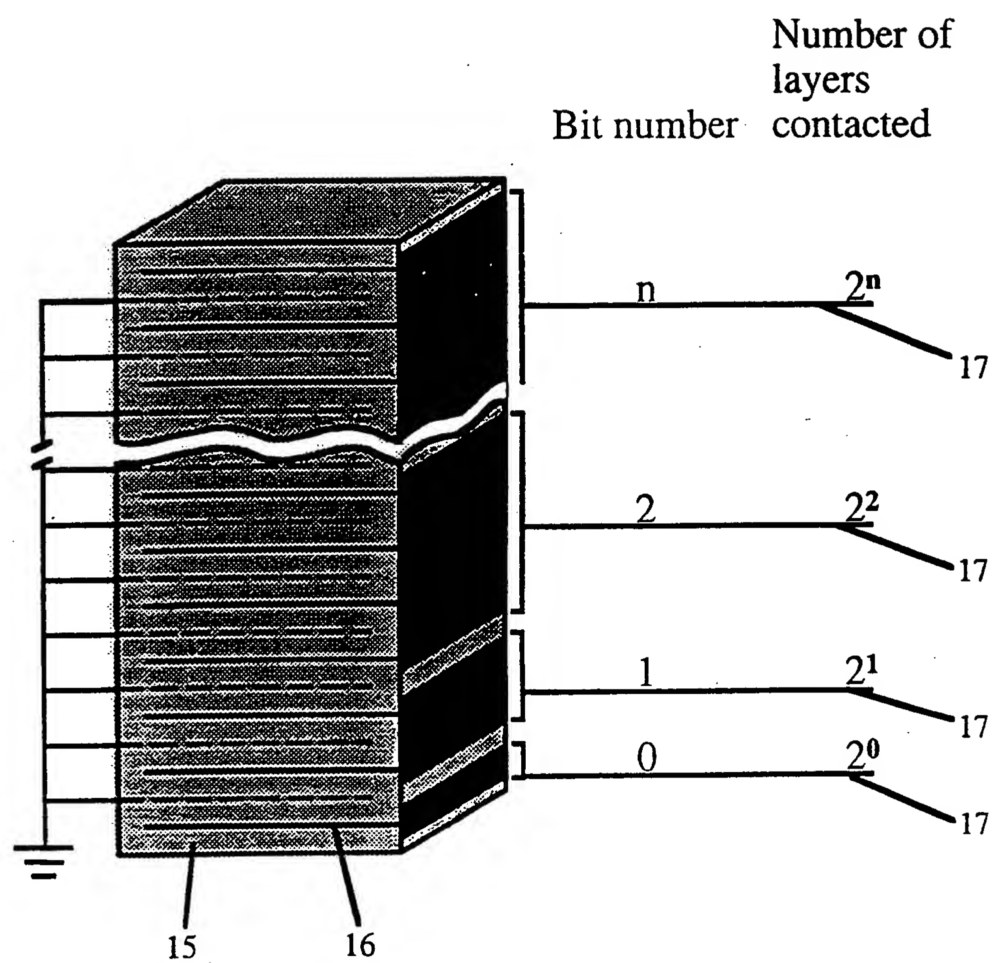



Figure 5


Number of layers contacted
Bit number
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$2^n$
17
2
$2^2$
17
1
$2^1$
17
0
$2^0$
17
15
16

Figure 6

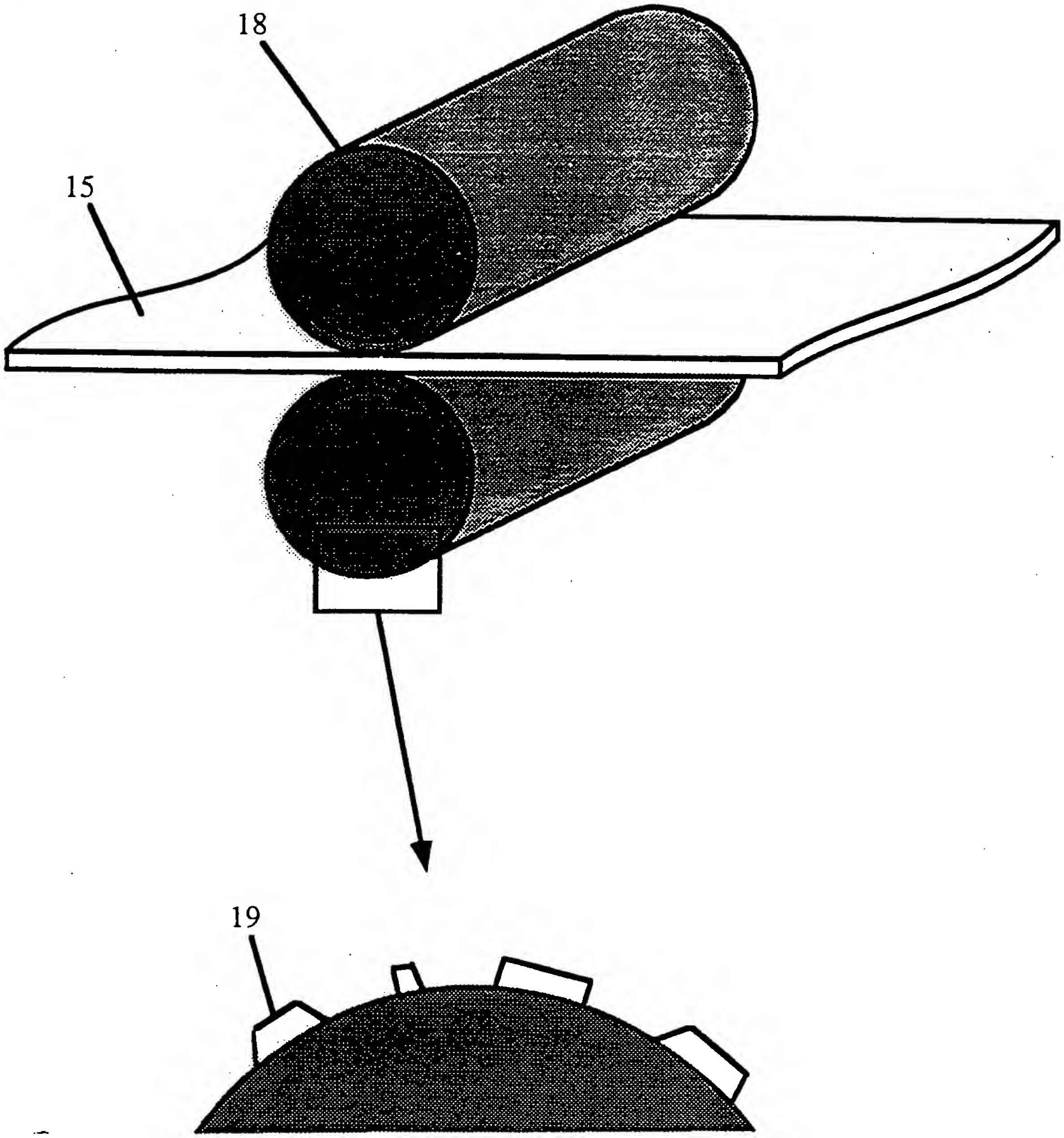


Figure 7

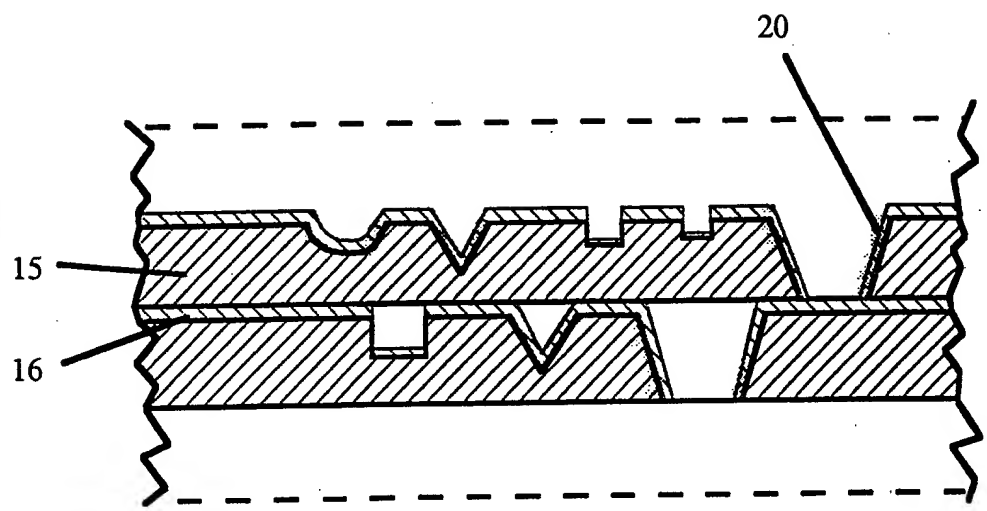


Figure 8

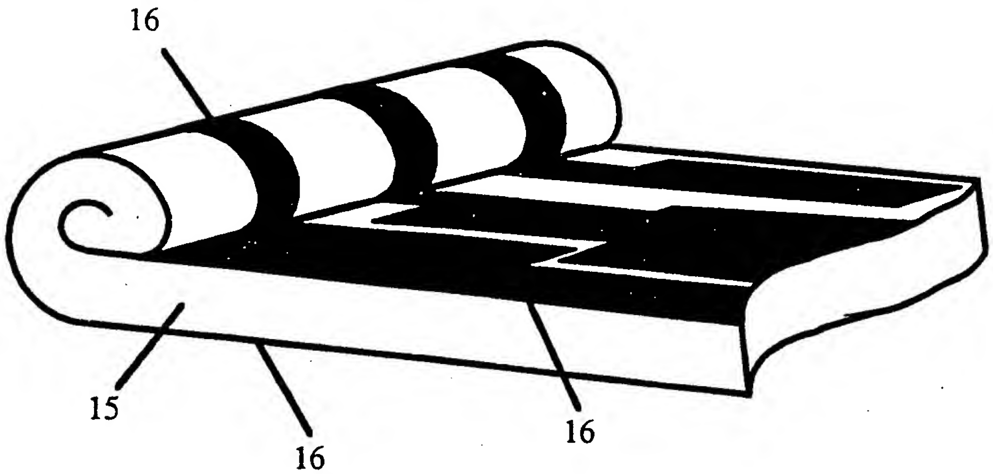


Figure 9

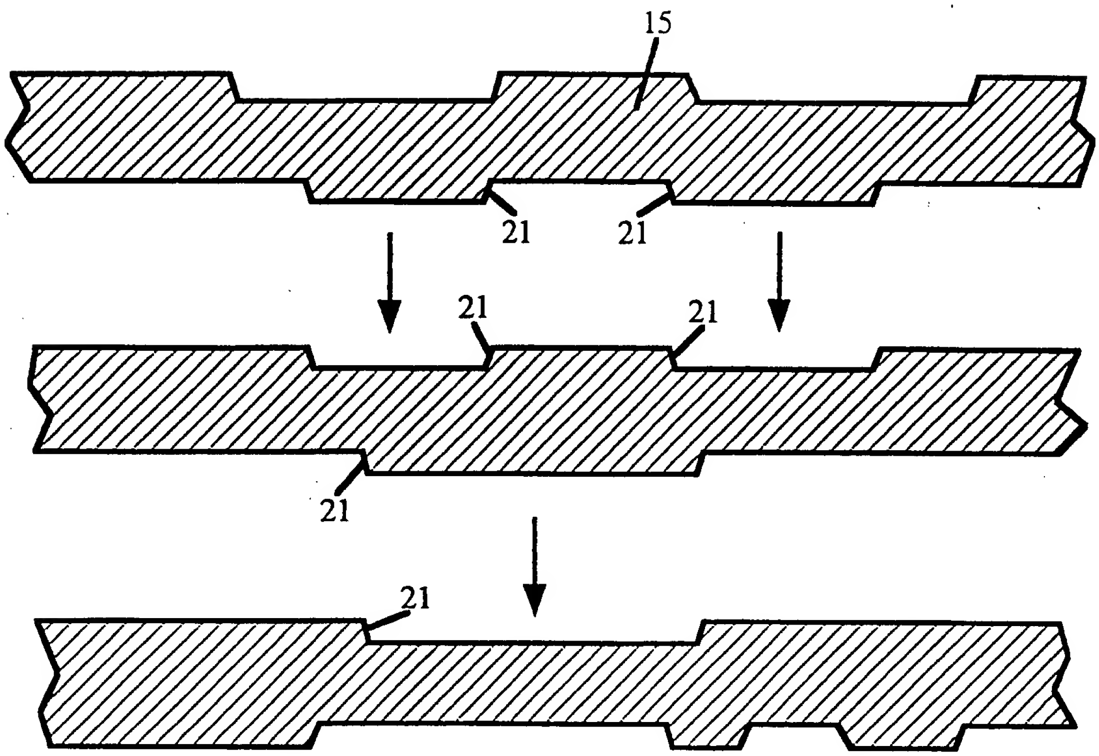


Figure 10

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 96/00391

## A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H02N 2/00, H01L 41/083
According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H02N, H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

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## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | GB 2179802 A (REIFENHAUSER GMBH & CO MASCHINENFABRIK), 11 March 1987 (11.03.87), page 1, line 49 - page 2, line 114<br>-- | 1-25 |
| X | Patent Abstracts of Japan, Vol 10,No 137, E-405, abstract of JP,A,61-1278 (NIPPON DENSHIN DENWA KOSHA), 7 January 1986 (07.01.86)<br>-- | 1-25 |
| X | DE 3531099 C2 (TOKYO JUKI INDUSTRIAL CO., LTD.), 19 April 1990 (19.04.90), column 1, line 61 - column 2, line 3<br>-- | 1 |

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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| Date of the actual completion of the international search | Date of mailing of the international search report |
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| Name and mailing address of the ISA/<br>Swedish Patent Office<br>Box 5055, S-102 42 STOCKHOLM<br>Facsimile No. +46 8 666 02 86 | Authorized officer<br><br>Håkan Sandh<br>Telephone No. +46 8 782 25 00 |

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 96/00391

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 9534944 A1 (PHILIPS ELECTRONICS N.V), 21 December 1995 (21.12.95), page 1, line 26 - page 3, line 7<br>-- | 1,10 |
| X | EP 0449048 A1 (ROCKWELL INTERNATIONAL CORPORATION), 2 October 1991 (02.10.91), column 2, line 44 - column 5, line 50<br>-- | 1,10-14, 17-21 |
| X | EP 0555828 A1 (ROCKWELL INTERNATIONAL CORPORATION), 18 August 1993 (18.08.93), abstract<br>-- | 1,10 |
| A | EP 0584775 A1 (CANON KABUSHIKI KAISHA), 2 March 1994 (02.03.94), column 3, line 29 - column 4, line 12<br>--<br>-------- | 1-28 |

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE96/00391

**Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

See next sheet!

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: 1-25

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 96/00391

I. Claims 1-25 directed to an actuator comprising a monolithic module with electrodes integrated in the electromechanical material and a method for fabricating an actuator based on replication of an geometrical pattern into a film including electromechanical material coated with an electrode layer.

II. Claim 26 directed to a method for fabricating an actuator based on replication of an geometrical pattern into a film where the shape is used for alignment of layers.

III. Claim 27 directed to a method for fabricating an actuator based on replication of an geometrical pattern into a film.

IV. Claim: 28 directed to a method for fabricating an actuator where the connection of electrode layers is accomplished with plastic deformation.

# INTERNATIONAL SEARCH REPORT
Information on patent family members

03/02/97

International application No.
PCT/SE 96/00391

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